

Nonstationary Interference Excision in Time-Frequency Domain Using Adaptive Hierarchical Lapped Orthogonal Transform for Direct Sequence Spread Spectrum Communications

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An adaptive hierarchical lapped orthogonal transform (HLOT) exciser is proposed for tracking, localizing, and rejecting the nonstationary interference in direct sequence spread spectrum (DSSS) communications. The method is based on HLOT. It utilizes a fast dynamic programming algorithm to search for the best basis, which matches the interference structure best, in a library of lapped orthogonal bases. The adaptive HLOT differs from conventional block transform and the more advanced modulated lapped transform (MLT) in that the former produces arbitrary time-frequency tiling, which can be adapted to the signal structure, while the latter yields fixed tilings. The time-frequency tiling of the adaptive HLOT can be time varying, so it is also able to track the variations of the signal time-frequency structure. Simulation results show that the proposed exciser brings significant performance improvement in the presence of nonstationary time-localized interference with or without instantaneous frequency (IF) information compared with the existing block transform domain excisers. Also, the proposed exciser is effective in suppressing narrowband interference and combined narrowband and time-localized impulsive interference.

Keywords and phrases: nonstationary interference excision, adaptive hierarchical lapped orthogonal transform, hierarchical binary tree, best basis selection, dynamic programming algorithm.

1. INTRODUCTION

Over the past several years, interference excision techniques based on time-frequency representations of the jammed signal have received significant attentions in direct sequence spread spectrum (DSSS) communications [1, 2, 3, 4]. The attraction of the time-frequency domain interference excision techniques is that they have the capability of analyzing the time-varying characteristics of the interference spectrum, while the existing time domain and transform domain techniques do not.

The time-frequency representation of a signal refers to

expanding the signal in orthogonal basis functions which give orthogonal tilings of the time-frequency plane. Herley et al. [5] use *time-frequency tile* of a particular basis function to designate the region in the time-frequency plane which contains most of that function's energy. The time-frequency tiles of the spread spectrum signal and the channel additive white Gaussian noise (AWGN) have evenly distributed energy, while that of the rapidly changing nonstationary interference have energy concentrated in just a few tiles. Consequently, it is easy to differentiate the interference from the signal and AWGN in the time-frequency domain. A good time-frequency exciser should be able to concentrate

the jammer energy on as few number of time-frequency tiles as possible in order to suppress interference efficiently with minimum signal distortion. This is equivalent to finding the best set of basis functions for the expansion of the jammed signal.

Conventional block transforms such as FFT and DCT result in fixed time-frequency resolution [6]. So do the modulated lapped transforms (MLT). They are often used to suppress narrowband interference. We show that they can also be used to suppress nonstationary interference by performing transforms after suitable segmentation of the time axis. However, as this method pays no attention to the signal time-frequency structures and splits the time axis blindly with equal segments, it does not always yield good results if the characteristics of the interference are not known in advance. The method proposed in [1] first decides the domain of excision, then cancels the interference in the appropriate domain. It excises nonstationary interference in the time domain. The method proposed in [2, 3] is based on the generalized Cohen's class time-frequency distribution (TFD) of the received signal from which the parameters of an adaptive time-varying interference excision filter are estimated. The TFD method has superior performance for interference with instantaneous frequency (IF) information such as chirp signals, but is less effective for pulsed interference without IF information such as time-localized wideband Gaussian interference. In [4], a pseudo time-frequency distribution is defined to determine the location and shape of the most energetic time-frequency tile along with its associated block transform packets (BTP) basis function. The interfering signal is expanded in terms of the BTP basis function in a sequential way until the resulting time-frequency spectrum is flat. The adaptive BTP provide arbitrary time-frequency tiling pattern which can be used to track and suppress time-localized wideband Gaussian interference. However, this method is not practical for real time processing as no fast algorithm is provided for selecting the BTP basis functions. In this paper, we propose an adaptive hierarchical lapped orthogonal transform (HLOT) which splits the time axis with unequal segments adapted to the signal time-frequency structures. The proposed adaptive HLOT has an arbitrary tiling in the time domain and has fixed frequency resolution at a given time. The tree structure associated with the desired pattern can be time varying, so it is able to track the variation of the signal time-frequency structure. A fast dynamic programming algorithm is utilized to search for the best basis which adapts to the jammed signal. The proposed exciser has superior performance for nonstationary time-localized interference with or without IF information and has performance comparable with traditional transform domain excisers for narrowband interference.

The paper is organized as follows. In Section 2, adaptive HLOT and best basis selection algorithm are introduced by means of hierarchical binary tree pruning. In Section 3, adaptive HLOT-based interference excision is explained in detail. In Section 4, simulation results using the proposed adaptive exciser are presented. Finally, in Section 5, conclusions are made.

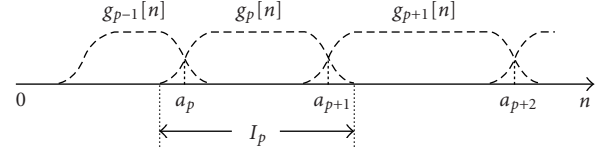


FIGURE 1: HLOT divides the time axis into overlapping intervals of varying sizes.

2. ADAPTIVE HLOT AND BEST BASIS SELECTION ALGORITHM

2.1. HLOT

HLOT is an effective multiresolution signal decomposition technique based on lapped orthogonal basis. It decomposes a signal into orthogonal segments whose supports overlap, as shown in Figure 1.

Here, $g_p[n]$ ($p \in \mathbb{Z}$) represent smooth windows which satisfy symmetry and quadrature properties on overlapping intervals [7], a_p ($p \in \mathbb{Z}$) indicates the position of $g_p[n]$ in the time axis, and I_p ($p \in \mathbb{Z}$) is the support of window g_p . The lapped orthogonal basis is defined from a Cosine-IV basis of $L^2(0, 1)$ by multiplying a translation and dilation of each vector with $g_p[n]$ ($p \in \mathbb{Z}$).

2.2. Criteria for best basis selection

A best lapped orthogonal basis can adapt the time segmentation to the variation of the signal time-frequency structure. Assuming f is the signal under consideration and D is a dictionary of orthogonal bases whose indices are in Λ ,

$$D = \bigcup_{\lambda \in \Lambda} B^\lambda, \quad (1)$$

where $B^\lambda = \{g_m^\lambda\}_{1 \leq m \leq N}$ is an orthonormal basis consisting of N vectors and λ is the index of B^λ . In order to facilitate fast computation, only the bases with dyadic sizes are considered. Suppose B^α is the basis that matches the signal best, that is, it satisfies the following condition:

$$\sum_{m=1}^M \frac{|\langle f, g_m^\alpha \rangle|^2}{\|f\|^2} \geq \sum_{m=1}^M \frac{|\langle f, g_m^\lambda \rangle|^2}{\|f\|^2} \quad (2)$$

$$\forall 1 \leq M \leq N, \lambda \in \Lambda, \lambda \neq \alpha.$$

The inner product $\langle f, g_m^\lambda \rangle$ is the lapped transform coefficient of f in basis g_m^λ . It is a good measure of signal expansion efficiency. The squared sum of $\langle f, g_m^\lambda \rangle$ reflects the approximation extent between f and the signal constructed with B^λ . The larger the squared sum of $\langle f, g_m^\lambda \rangle$, the better B^λ matches the signal. Condition (2) is equivalent to minimizing a Schur concave sum $C(f, B^\lambda)$ [8]:

$$C(f, B^\lambda) = \sum_{m=1}^M \Phi \left(\frac{|\langle f, g_m^\lambda \rangle|^2}{\|f\|^2} \right) \quad \forall 1 \leq M \leq N, \quad (3)$$

where Φ is an additive concave cost function.

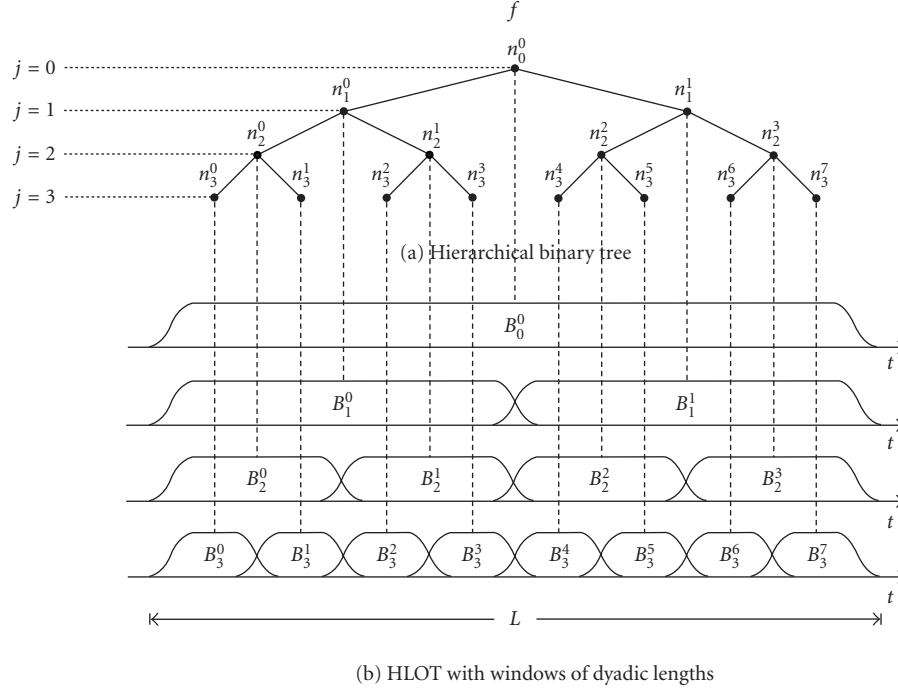


FIGURE 2: HLOT is organized as subsets of a binary tree.

Several popular concave cost functionals are the Shannon entropy, the Gaussian entropy and the l^p ($0 < p \leq 1$) cost [8, 9, 10]. Coifman and Wickerhauser use Shannon entropy for best basis selection, while Donoho adopts l^p cost for *minimum entropy segmentation* since the l^p entropy indicates a sharper preference for a specific segmentation than the other entropies [9]. The objective of the HLOT is virtually a problem of *minimum entropy segmentation*, so we choose l^p cost function $\Phi(x) = x^{1/2}$. Therefore, the best basis B^α can be found by minimizing $C(f, B^\lambda)$:

$$C(f, B^\alpha) = \min_{\lambda \in \Lambda} C(f, B^\lambda) = \min_{\lambda \in \Lambda} \sum_{m=1}^N \frac{|\langle f, g_m^\lambda \rangle|}{\|f\|}. \quad (4)$$

Choice of l^p cost can be further justified in Figure 7 of Section 4.

2.3. Adaptive HLOT and fast dynamic programming algorithm

The objective of the proposed adaptive HLOT is to decompose the considered signal in the best lapped orthogonal basis. First, an HLOT is performed to f with all the bases in the dictionary. This is depicted in Figure 2 with the library D being organized as subsets of a binary tree to facilitate fast computation.

Suppose J is the depth of the binary tree, and the length of signal f is L . Here, we consider dyadic split of time axis, so L should be the power of two, that is,

$$L = 2^J; \quad (5)$$

f should be padded with zeros if (5) is not satisfied. Each tree node n_j^p ($0 \leq p \leq 2^j - 1$, $0 \leq j \leq J - 1$) represents a subspace of the considered signal. Each subspace is the orthogonal direct sum of its two children nodes n_{j+1}^{2p} and n_{j+1}^{2p+1} . Basis B_j^p corresponds to the lapped orthogonal basis over interval p ($0 \leq p \leq 2^j - 1$) of the 2^j intervals at level j of the tree. It is given by

$$B_j^p = \left\{ g_p(n) \sqrt{\frac{2}{l_p}} \cos \left[\frac{\pi}{l_p} \left(k + \frac{1}{2} \right) \times \left(n - pl_p + \frac{1}{2} \right) \right] \right\}_{0 \leq k, n < l_p, 0 \leq p \leq 2^j - 1, 0 \leq j \leq J-1}, \quad (6)$$

where $l_p = L/2^j$. The library D is the union of all the lapped orthogonal bases which corresponds to all the subspace of the signal:

$$D = \bigcup_{\substack{0 \leq j \leq J-1 \\ 0 \leq p \leq 2^j - 1}} B_j^p. \quad (7)$$

The fast dynamic programming algorithm introduced by Coifman and Wickerhauser [8] is employed to find the best basis. It is a bottom-up progressively searching process. Suppose O_j^p is the best basis at node n_j^p , then the dynamic programming algorithm can be described as follows.

- (1) At the bottom of the tree, each node is not subdecomposed, so $O_j^p = B_j^p$.

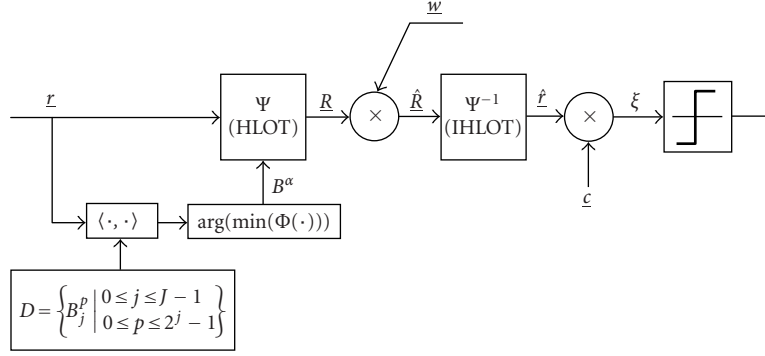


FIGURE 3: DSSS receiver employing adaptive HLOT excision and detection.

(2) Let $j = J - 1$, then

$$O_j^p = \begin{cases} O_{j+1}^{2p} \cup O_{j+1}^{2p+1} & \text{if } C(f, O_{j+1}^{2p}) + C(f, O_{j+1}^{2p+1}) < C(f, B_j^p), \\ B_j^p & \text{if } C(f, O_{j+1}^{2p}) + C(f, O_{j+1}^{2p+1}) \geq C(f, B_j^p). \end{cases} \quad (8)$$

(3) Let $j = J - 2$ and repeat (2) until the root gives the best basis of f .

This algorithm is capable of tuning the hierarchical transform to the signal structure under consideration. A signal of L points can be expanded in $O(\log L)$ operations, and the best basis selection may be obtained in an additional $O(L)$ operations [8].

3. ADAPTIVE HLOT-BASED INTERFERENCE EXCISION

3.1. Adaptive HLOT-based DSSS receiver model

Figure 3 illustrates the block diagram of the DSSS receiver employing the proposed adaptive HLOT exciser algorithm.

Assume that the received signal is sampled at the chip rate of the PN sequence and partitioned into disjoint length- L data segments corresponding to the individual data bits. The $L \times 1$ input vector \underline{r} consists of the sum of L samples from the spread data bit with those from the additive noise and interference, expressed as

$$\underline{r} = \underline{s} + \underline{n} + \underline{j}. \quad (9)$$

Here, each data bit is spread by a full-length PN code, that is,

$$\underline{s} = d(k)\underline{c}, \quad (10)$$

where $d(k)$ is the current data bit with $d(k) \in \{-1, +1\}$, and \underline{c} is the length- L PN code; vector \underline{n} represents zero mean AWGN samples with two-sided power spectral density $N_0/2$; vector \underline{j} represents time-varying nonstationary interference samples.

3.2. Adaptive HLOT-based interference excision algorithm

Adaptive HLOT-based interference excision is performed as shown in Figure 3. The inner products between \underline{r} and all the bases in D are computed first and the best basis B^α is selected using fast dynamic programming algorithm introduced in Section 2. Then \underline{r} is transformed to the frequency domain by HLOT using B^α . The transform domain coefficients can be expressed as

$$\underline{R} = \Psi \underline{r}, \quad (11)$$

where Ψ represents $L \times L$ forward HLOT matrix. Since the spectra of \underline{s} and \underline{n} are flat, while that of \underline{j} is sharp and narrow, the transform domain coefficients with large amplitude correspond to the interference. For excision, these coefficients are either entirely eliminated or their power is reduced by clipping through the application of threshold or multiplying by a weighting function [11]. Here, the interference coefficients are replaced by zeros. If no interference exists, \underline{R} is passed without modification. The excised coefficients $\underline{\hat{R}}$ are given by

$$\underline{\hat{R}} = \text{diag}(\underline{w})\underline{R}, \quad (12)$$

where the values of the excision vector \underline{w} are either 0 or 1 and $\text{diag}(\cdot)$ denotes $L \times L$ matrix with diagonal elements corresponding to the excision vector. The excised coefficients are then transformed back to time domain by inverse HLOT and the reconstructed received signal $\underline{\hat{r}}$ is given by

$$\underline{\hat{r}} = \Psi^{-1} \underline{\hat{R}}, \quad (13)$$

where Ψ^{-1} represents $L \times L$ inverse HLOT matrix. Assuming perfect synchronization, the decision variable ξ can be given by correlating $\underline{\hat{r}}$ with PN code sequence \underline{c} :

$$\xi = \underline{c}^T \underline{\hat{r}}. \quad (14)$$

Finally, the transmitted data bit is determined by putting ξ through a threshold device with the decision boundary set to zero.

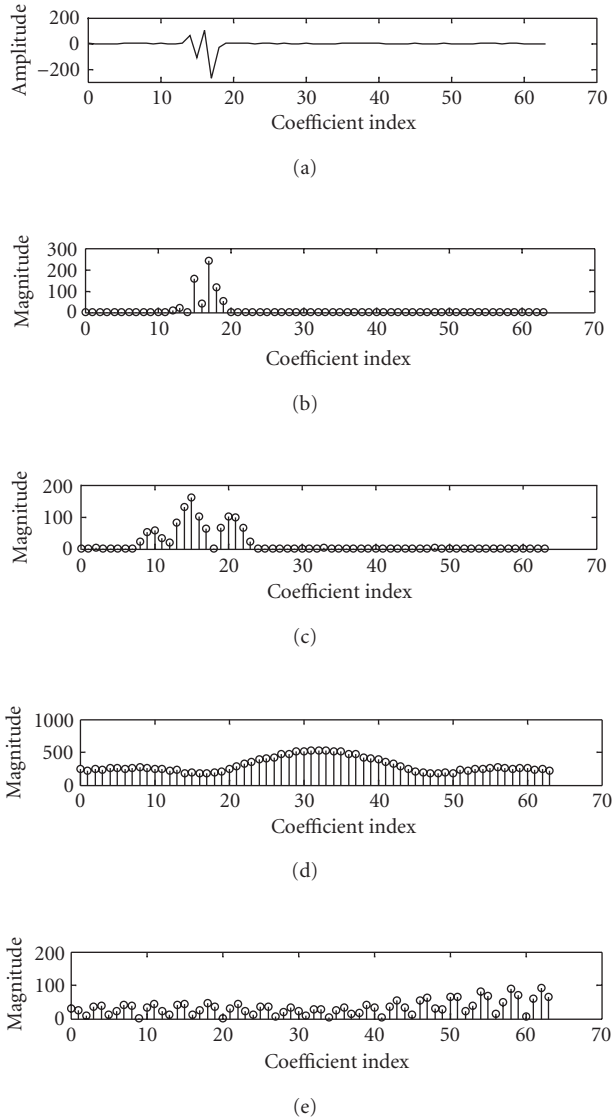


FIGURE 4: Comparison of basis expansions of nonstationary signal. (a) The time-localized interference signal, SNR=18 dB, ISR=20 dB. (b) Adaptive HLOT basis expansion. (c) MLT basis expansion. (d) FFT basis expansion. (e) DCT basis expansion.

The main advantage of the proposed adaptive HLOT exciser is that the time-frequency tiling of the best basis can be adapted to the variations of the received signal structure. It is especially suitable for tracking, localizing, and suppressing nonstationary interference.

4. PERFORMANCE EVALUATIONS

To evaluate the interference rejection capability of the proposed adaptive HLOT exciser in DSSS communications, a simulation packet was developed based on Stanford University's signal processing software. The performance of the proposed adaptive HLOT exciser along with MLT-, FFT-, and

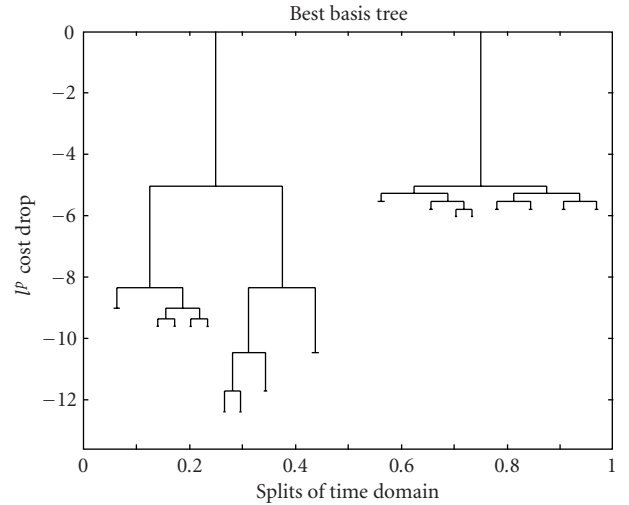


FIGURE 5: The best basis tree of the adaptive HLOT of nonstationary interference.

DCT-based excisers with fixed time resolution of 8 samples and conventional 64-point FFT- and DCT-based excisers is evaluated. A 63-chip maximum length PN code was used to spread the input data stream. A BPSK modulation and an AWGN channel were assumed. Four types of interferences are considered: a nonstationary time-localized wideband Gaussian jammer, a nonstationary time-localized chirp jammer, a single-tone jammer, and a combined single-tone and time-localized impulsive jammer.

Nonstationary time-localized wideband Gaussian interference (without IF information)

For the nonstationary time-localized wideband Gaussian jammer that is randomly switched with a 10% duty cycle, Figure 4 compares the magnitude responses of the adaptive HLOT, MLT with time resolution of 8 samples, 64-point FFT, and DCT. The signal-to-noise ratio (SNR) is 18 dB and the interference-to-signal ratio (ISR) is 20 dB. It is clear that the adaptive HLOT is capable of concentrating the jammer energy to the least number of spectrum coefficients. Therefore, it allows minimum number of frequency bins to be excised and causes minimum signal distortion.

Figure 5 displays the best basis tree associates with the adaptive HLOT of the nonstationary interference. Figure 6 depicts the time-frequency tiling of the best basis that is adapted to the jammed signal time-frequency structures. It is shown that the proposed adaptive HLOT produces an arbitrary time axis split which reflects the variations of the signal structure. Figure 7 compares the error energy of signal approximation by two sets of best basis which are selected by l^p cost and Shannon entropy criteria, respectively. It is obvious that the l^p cost-based best basis representation of the signal shows less error.

Figure 8 shows the BER performance of the proposed adaptive HLOT exciser along with the block transform

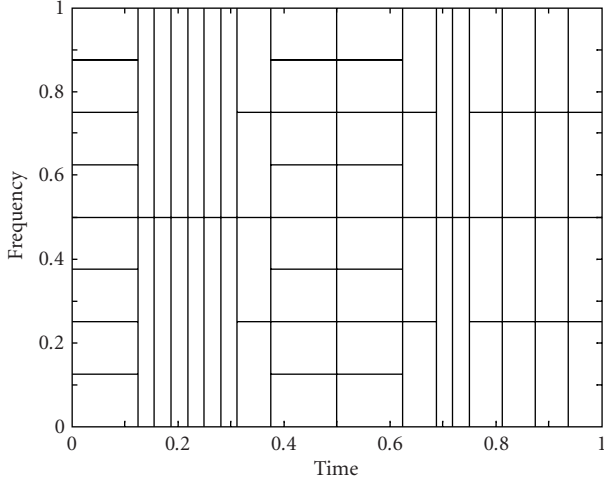


FIGURE 6: The adaptive HLOT tiling of time-frequency plane for nonstationary interference.

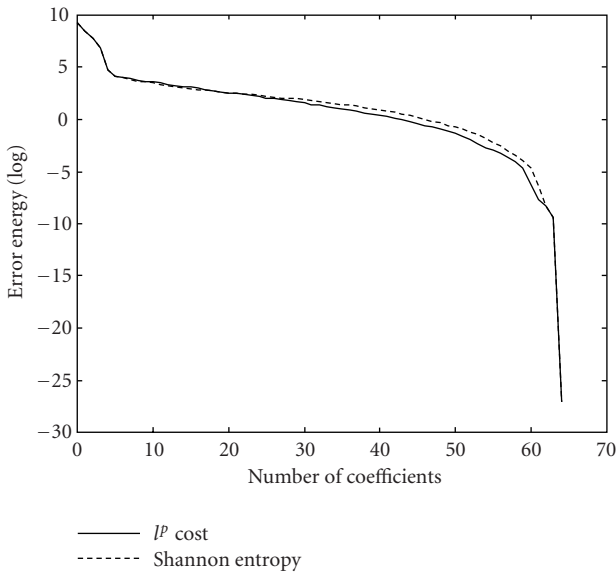


FIGURE 7: Compression curves for the adaptive HLOT coefficients corresponding to l^p cost and Shannon entropy.

domain excisers and the MLT domain exciser. The ISR is 20 dB. As can be seen from the figure, the adaptive exciser yields the best performance compared with the other excisers. Adaptive HLOT is superior to 8 points/window FFT, DCT, and MLT in that the former provides signal adaptive time axis division while the latter split the time axis blindly.

Figure 9 illustrates the BER performance of the excision-based receivers as a function of ISR. The SNR is 8 dB. As the performance of the adaptive HLOT does not deviate significantly from the ideal BER performance in AWGN over all

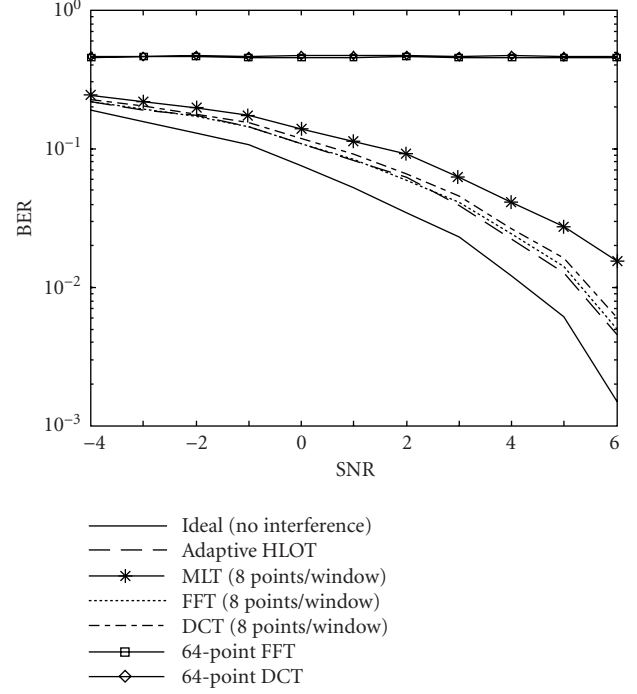


FIGURE 8: BER curves for nonstationary wideband Gaussian interference (10% duty cycle) as a function of SNR under ISR of 20 dB.

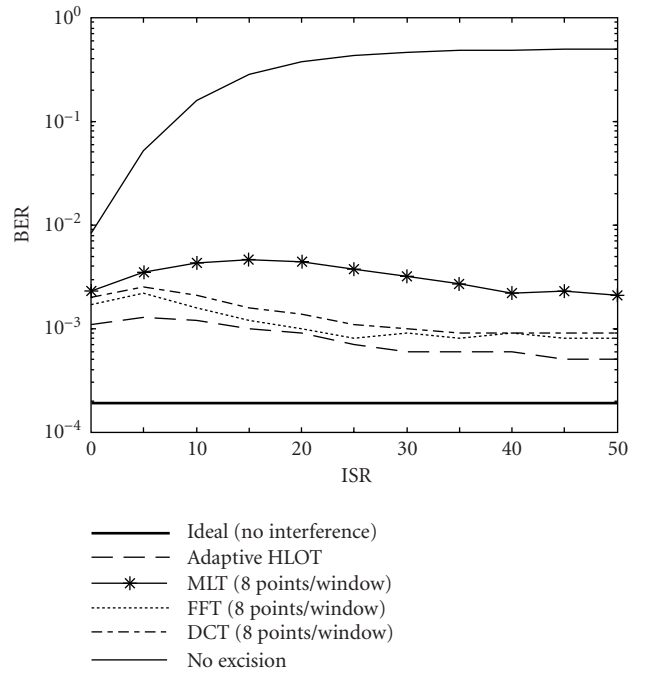


FIGURE 9: BER curves for nonstationary time-localized wideband Gaussian interference (10% duty cycle) as a function of ISR under SNR of 8 dB.

jammer powers, the robustness of the adaptive HLOT excision relative to the jammer power is demonstrated.

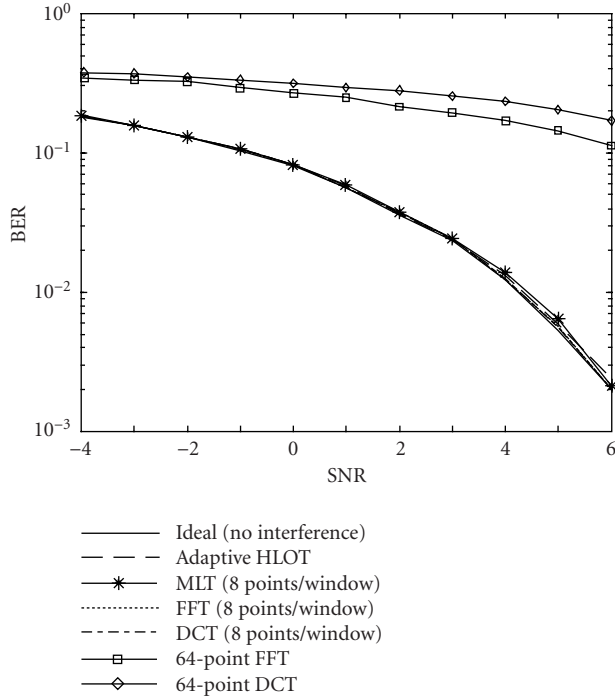


FIGURE 10: BER curves for nonstationary time-localized chirp interference (10% duty cycle) as a function of SNR under ISR of 20 dB.

Nonstationary time-localized chirp interference (with IF information)

Figure 10 displays the BER curves for the case of a pulsed chirp jammer as a function of SNR. The jammer is randomly switched with a 10% duty cycle and the jammer chirp-rate is 0.5. The ISR is 20 dB. Both the adaptive HLOT and the 8 points/window FFT, DCT, and MLT yield nearly optimal performance. Figure 11 shows the BER curves as a function of ISR under the SNR of 8 dB. The adaptive HLOT excision-based receiver shows more insensitivity to the variations of the jammer power than the FFT, DCT, and MLT excision-based ones.

Narrowband interference

A single-tone interference with tone frequency of 1.92 rad and uniformly distributed random phase ($\theta \in [0, 2\pi]$) is considered. The ISR is 20 dB. The time-frequency tiling of the best basis associated with the jammed signal is shown in Figure 12. As can be seen from Figure 12, the proposed HLOT virtually becomes a block transform (type-IV discrete cosine transform) with fixed frequency resolution in this scenario. Therefore, it performs comparably with conventional block transform domain excisers with block sizes of 64, as shown in Figure 13. On the other hand, the MLT, FFT, and DCT with smaller block sizes cannot guarantee good performance.

The BER performance of the adaptive HLOT excision-based receiver for a single-tone interferer with varying fre-

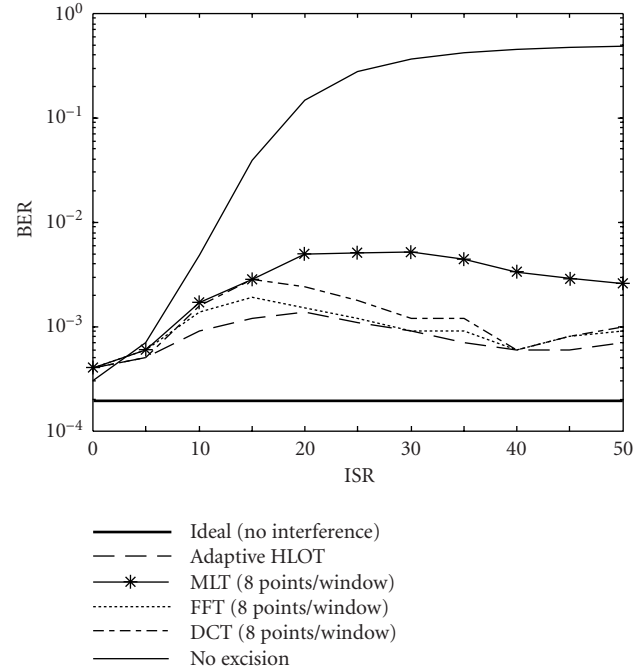


FIGURE 11: BER curves for nonstationary time-localized chirp interference (10% duty cycle) as a function of ISR under SNR of 8 dB.

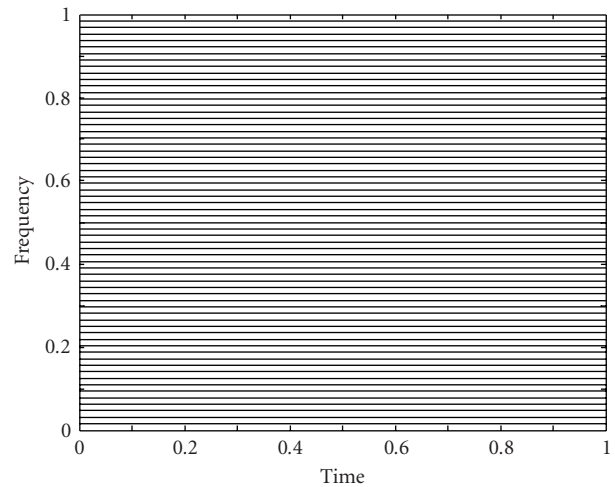


FIGURE 12: The adaptive HLOT tiling of the time-frequency plane for single-tone interference under SNR of 8 dB.

quency is displayed in Figure 14. It is seen from the figure that the adaptive HLOT excision-based receiver is very robust to the variations of the input signal.

Combined narrowband and time-localized impulsive interference

A single-tone interference with tone frequency of 1.92 rad and uniformly distributed random phase ($\theta \in [0, 2\pi]$) plus time-localized wideband Gaussian interference with 10%

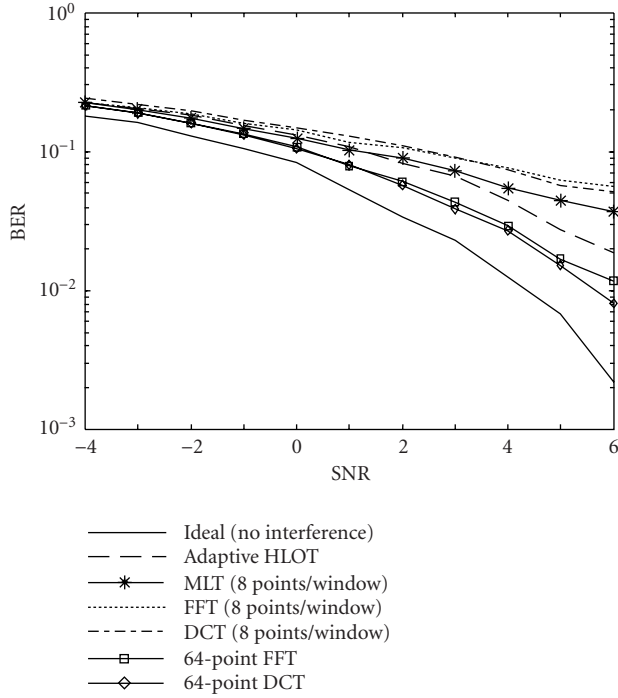


FIGURE 13: BER curves for single-tone interference (ISR=20 dB, tone frequency = 1.92 rad).

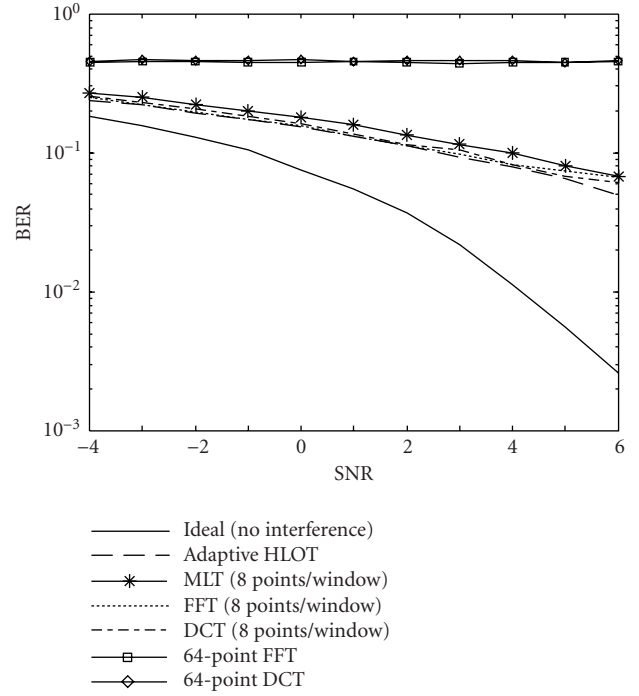


FIGURE 15: BER curves for combined single-tone ($w_3 = 1.92$) and time-localized wideband Gaussian interference (10% duty cycle, ISR=20 dB).

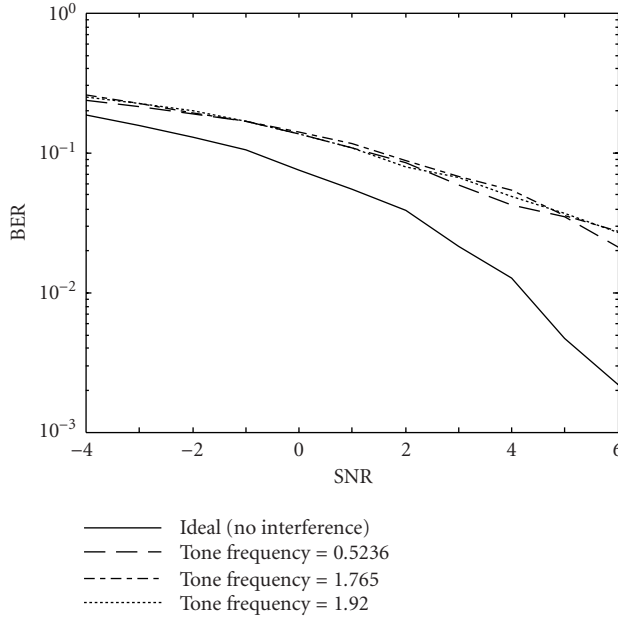


FIGURE 14: BER curves of adaptive HLOT exciser for single-tone interference (ISR=20 dB, $w_1 = 0.5236$ rad, $w_2 = 1.765$ rad, $w_3 = 1.92$ rad).

duty cycle are considered. The power ratio of single-tone interference to time-localized interference is -8 dB and the total ISR is 20 dB. Figure 15 displays the BER results as a func-

tion of SNR. It is shown that the adaptive HLOT exciser is more effective than the other transform domain excisers.

5. CONCLUSIONS

An adaptive time-frequency domain nonstationary interference exciser using HLOT is presented in this paper. It takes the time-varying properties of the nonstationary interference spectrum into consideration and adaptively changes its structure according to the variations of the interference signal. Since the library of lapped orthogonal bases can be set up in advance and a fast dynamic programming algorithm for best basis selection is employed, real time interference excision is feasible. Simulation results demonstrate the efficiency of the proposed adaptive exciser for excising nonstationary interference. It is also shown that the proposed adaptive exciser is capable of suppressing narrowband and combined narrowband and time-localized interference.

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